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WELDING RESEARCH

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ASSOCIATION NOTES

On the next three pages of this issue we have printed two memoranda dealing with the progress of work of the Technical Commission number I0/11 of the International Institute of Welding. We feel that these memoranda will be of considerable interest to many readers in this country.

Meeting of the International Institute of Welding Commission No. 10/11 on Residual Stresses and Stress Relieving held in Göteborg, Sweden, on 8th-12th September, 1952

The International Institute of Welding was inaugurated in 1948. An account of the activities of the I.I.W. during the past four years has been published in "Sheet Metal Industries," Vol. 29, No. 307, November, 1952. This account includes an outline of the work being undertaken by the Technical Commissions of the I.I.W. which have been appointed to study problems and developments in welding of common interest to the supporting countries. One of these commissions, No. 10/11, under the chairmanship of Dr. Richard Week, is dealing with problems affecting the stress relieving of welded structures, and is also considering the influence of residual welding stresses on the behaviour of such structures.

Following the recent annual meeting of the I.I.W. in Goteborg, Sweden, Dr. Week prepared a memorandum which summarises the progress made by Technical Commission No. 10/11. One of the first projects undertaken by the commission was to establish an enquiry on stress relieving practice and regulations in the various countries. The results of this enquiry have been analysed in a memorandum prepared by three members of the commission, L. E. Benson (U.K.), M. Hansen (Denmark) and H. Harris (U.K.).

PROGRESS OF WORK OF COMMISSION No. 10/11. *By Dr. R. Week.*

DEFINITIONS

On the basis of the document submitted by the Swedish Delegate, Mr. R. Gunnert, a discussion took place on terms and definitions which are of particular importance to the work of the Commission. Definitions were agreed as follows:

Residual Stress (contrainte résiduelle)
Stress remaining in a structural member as a result of thermal or mechanical treatment or both.

Residual Welding Stress (contrainte résiduelle de soudure)
Residual stress due to welding and remaining after the welding is completed and the joint has cooled down.

Welding Stress (contrainte de soudage)
Stress present whilst welding is proceeding.

Reaction Stress (contrainte de bridage)
That part of the residual welding stress caused by external restraint.

Longitudinal Stress (contrainte longitudinale)
Stress in the direction of the weld.

Transverse Stress (contrainte transversale)
Stress transverse to the direction of the weld and in a plane approximately parallel to the surface of the weld.

Perpendicular Stress (contrainte perpendiculaire)
Stress transverse to the direction of the weld and in a plane approximately perpendicular to the face of the weld.

Stress Relieving Heat Treatment at low Temperature

The problem of the efficacy of stress relieving heat treatment at low temperature (200-300 deg. C.) has been on the Agenda of the Commission since its inception. At the Oxford meeting it was decided to set up a Sub-Committee for further detailed study of this question. Two reports were presented to the Commission, namely, "To what extent does stress relieving occur at 200-300 deg. C.", by R. Gunnert, and "Low-Temperature Stress Relieving of Mild Steel Welded Structures," by L. E. Benson and S. J. Watson. On the basis of these reports, the Commission reached the following conclusions:

1. Treatment at 200-300 deg. C. results in appreciable reduction of the highest stresses in a welded structure.
2. The average level of stress will be slightly reduced after this treatment.
3. The low-temperature treatment is, however, not so effective as the more normal treatment at 600-650 deg. C., but in the opinion of the Commission the low-temperature treatment could, with advantage, be considered for those constructions that cannot be given the higher temperature treatment.

With these conclusions the Commission considers its work on the problem of the efficacy of low-temperature stress relieving to be concluded, and the Sub-Committee investigating this problem was disbanded.

International Enquiry on Stress Relieving

An international enquiry on stress-relieving practices and regulations in different countries was conducted during the first year of the Commission's existence. The results were tabulated and were then used by a Sub-Commission in the preparation of a memorandum. This was discussed at the meeting in Göteborg, and after discussion the Commission decided to recommend to the Governing Council that the memorandum be published by all member societies. The memorandum is included at the end of this report.

Methods for Residual Stress Measurements

It is clear that all experimental work on residual stresses ultimately involves the problem of measurement of these stresses. The Commission recognised at the very beginning of its work that considerable sums of money were expended annually in different countries on residual stress investigations, but that the full benefit of this expenditure was not always obtained. In many cases the method used for measuring residual stresses was open to serious criticism and the results obtained were to some extent invalidated. Different investigators using different methods for the investigation of the same problem, would often arrive at completely contradictory results. It was realised that the method of measurement was one of the basic variables in all residual stress investigations, and in order to make investigations carried out in different countries more easily comparable, this variable would have to be eliminated. It was the aim of the Commission to correct this state of affairs by recommending one, or at any rate a small number of methods for measuring residual stresses which could be considered to give equivalent results, for international use. As a first step an investigation was initiated in which identical plates containing identical states of stress would be measured by different methods in different countries. The results of this investigation have been reported to the Commission, and they show that different methods will give different results. In view of the fact, however, that in this investigation certain difficulties arose in the manufacture of the test plates which could not be anticipated and which might have given rise to differences in the states of stress in the test plates, it has been decided that this investigation should be repeated in such a way that mechanical stress measurements can be compared with measurements carried out by the X-ray method. The test plates will be 1 in. thick and 12 in. square and residual stresses will be introduced by torch heating along the centre line of the plate. The test plates will be manufactured in the U.S.A. where the X-ray stress measurements will be carried out. They will then be despatched to different European countries for the mechanical methods of measurement.

Despite the difficulties inherent in this type of investigation, extremely good progress has been made towards the acceptance of a standard method of measuring residual stresses to recommend for international use. On the basis of experi-

mental work which extended over two years, the Commission has come to the conclusion of recommending a method developed by the Swedish member of the Commission, Mr. R. Gunnert, and in fact most of the countries participating in the work of the Commission have now bought the instrument and have carried out investigations with it. Mr. Gunnert has been requested to work out detailed rules for the use of this method, and his recommendations are contained in a document entitled, "Directions for Application of a Method of Gauging Residual Stresses." It is hoped that with the aid of this document it will be possible for investigators in all countries to carry out residual stress measurements by a standard procedure.

At the Oxford meeting the Commission had decided that the method should be tried in a number of countries before it was to be recommended for international use, and these trials, reports of which were available at the Göteborg meeting, have been eminently satisfactory. In a report submitted by O. Forsman (Sweden), entitled "Determination of Residual Stresses in a Weld by means of the method developed by Gunnert," it is shown that different investigators would obtain the same results if they followed the Gunnert procedure, and it is also shown that the procedure can be applied successfully by operators with no special training.

A satisfactory comparison of the Gunnert method with stress measurements effected by electric resistance strain gauges was carried out in Finland by Professor Eiro and Mr. Hirvonen. The report of this work was submitted by the Finnish delegate to the Commission, Mr. H. Branders, who had initiated the work. Stress measurements were carried out both on tensile specimens and on welded plates. The investigations proved that the Gunnert method was absolutely reliable.

The originator of the method, Mr. Gunnert, carried out an investigation in order to determine whether the method could be successfully used in an environment other than the laboratory. His report entitled "Residual Stresses in a Welded Ship's Hull" showed that this method offers satisfactory accuracy also under conditions which cannot be considered to be very favourable for precision measurements.

On the basis of these reports the Commission came to the conclusion to recommend Mr. Gunnert's method as an international standards method for the measuring of residual stresses.

Residual Stresses and Brittle Fracture

The difficult and complex problem of the effect of residual stresses on brittle fracture in welded structures which has engaged the Commission's attention ever since its beginning is being actively pursued, and certain concrete proposals for experimental investigations submitted by a Sub-Commission charged with this task came up for discussion. It was decided that a number of countries should proceed with investigations in which plate specimens into which residual stresses are introduced by welding should be broken by impact in large capacity impact testing machines in order to determine whether residual stresses have any effect on the impact resistance of the material in the presence of a notch.

A further proposal envisaging the use of thick pressure vessels, to be destroyed either by dropping from a height or by internal explosion, has been referred to the Sub-Commission for further consideration. The object of this latter proposal is really twofold, namely, to determine whether residual stresses have any effect on brittle fracture under shock loading, and secondly to determine the efficacy of different stress-relieving treatments, such as heat treatment in a furnace, peening, local stress relieving, etc., on the elimination of the deleterious effect of residual stresses, if any. It is also hoped that certain other investigations planned in different countries for the elucidation of this problem will have been concluded before the next meeting of the Commission.

Future Work

The Commission gave some consideration to its Agenda for next year's meeting.

(i) *Low-Temperature (Linde-Method) Stress Relieving.* It was decided to obtain up-to-date information on the stress relieving procedure invented in the U.S.A. and known as low-temperature stress relieving or the Linde-method and to have a thorough discussion on the basis of the available information on both the efficiency of the method and the possible dangers of its use. Questions which require further elucidation in connection with this stress relieving method are:

1. Up to what plate thickness is the method efficacious in reducing residual stresses?
2. Whilst it can be shown that considerable stress relief is obtained in plates joined by one butt weld, there is some doubt whether similar beneficial results can be obtained in more complex constructions where there are intersecting butt welds and possibly fillet welds.
3. The question as to whether this method of heating and quenching has any deleterious effect on the properties of the material must also be considered.

(ii) *Stress Relieving of Steels other than Mild Steel.* The attention of the Commission has so far been confined to problems arising in welded structures constructed from mild steel, and it has been suggested that other steels such as stainless and 1·2 per cent. molybdenum as used for high temperature steam lines should also be considered. It was therefore decided that stress relieving of steels other than mild steel should be put on the Agenda of next year's meeting.

(iii) *Influence of Welding Sequence on Residual Stresses.* The problem as to the extent of stress diminution by varying certain welding sequences and procedures is to be put on next year's Agenda, and the Swiss and French delegates have undertaken to prepare preliminary statements.

(iv) *Ageing.* M. Gerbeaux submitted a paper entitled "La sensibilité au vieillissement des aciers sous de faibles taux d'écrouissage et ses conséquences." In this paper the author draws the attention of the Commission to the fact that different ageing properties may result in different effects of residual stresses. During the cooling of a weld a certain amount of plastic deformation is produced which may lead to acceleration of ageing, and even if in identical structures identical states of residual stress are produced it is conceivable that in consequence of the different ageing properties identical states of residual stress would have different effects. The French delegate undertook to carry out further investigations into this problem.

MEMORANDUM ON STRESS RELIEVING

Summary of stress-relieving regulations and practices, compiled by L. E. Benson (U.K.), M. Hansen (Denmark) and H. Harris (U.K.)

During the meetings at Göteborg the Commission decided to forward to the Governing Council of the International Institute of Welding (I.I.W.) the memorandum prepared and based on the replies received from the delegates to a questionnaire on stress relieving regulations and practices in different countries (see below for summary of replies).

The Commission recommended that this memorandum be published and drew attention particularly to the following points:

1. Although stress relieving is required by certain regulations and specifications for certain welded structures, there is uncertainty as to whether a stress-relieving treatment is of real benefit in regard to the behaviour of the parts in service.
2. The conditions which determine whether stress relieving must be given or not are sometimes contradictory.

The Commission considers that this state of affairs is very unsatisfactory and draws attention to the need for

wider dissemination of available information and experience and for further investigations leading to a better understanding of the phenomena involved and the conditions under which stress relieving is necessary.

The Commission further recommends that the necessary steps should be taken by the Governing Council of the I.I.W. to acquaint the International Standards Organisation (I.S.O.) of the present state of affairs and to enquire whether the I.S.O. will consider taking action to bring about unification of specification requirements in different countries.

It must be clearly understood in this context that the Commission itself by its terms of reference is not in a position to make recommendations for international standardization. If, however, the Commission were officially entrusted with this task by the I.I.W. and the I.S.O., the Commission would undoubtedly be prepared to work out proposals on stress relieving with recommendations for international standardization.

Summary of Replies to Questionnaire on Stress Relieving Regulations and Practice in Different Countries

The following notes are an attempt to make a critical review of replies which members of Commission 10-11 of the I.I.W. sent in response to questions regarding stress relieving practice in their countries.

The notes refer particularly to heat treatment for the relief of internal stress rather than for other purposes, such as the reduction of hardness in the weld or in the metal adjacent to the weld.

Regulations Governing Stress Relieving

Replies were received from Belgium, Denmark, England, Finland, France, Norway, Sweden, Switzerland and the United States. In seven of these countries it was reported that there were official or semi-official regulations in force which require stress relieving of some welded structures. Authority is given to such requirements by government regulations and by clauses in specifications issued by the Standards Institutes of some countries. Stress relieving may also be enforced through the regulations of important Inspecting Bodies and Insurance Companies. In Belgium the "Institut de la Normalisation" recommends stress relieving under certain circumstances but the requirements are not mandatory. In France there appear to be no official regulations or recommendations regarding stress relieving.

Applications where Stress Relieving may be Required

It would appear to be virtually universal practice to stress relieve welded boilers and other pressure vessels within certain limitations in regard to dimensions and service conditions. In countries where codes of practice or specifications have been formulated stress relieving clauses are included. In other countries it is regarded as good practice.

Welded steam-pipe joints for high-temperature high-pressure service are also treated as pressure vessels in some countries, but it is not clear how far this is general practice. Where stress relieving is applied to alloy-steel steam pipes, it is also not clear how far the object is to relieve welding stresses as distinct from ensuring satisfactory hardness in the metal adjacent to the weld. In view of the importance of steam pipes more precise information might usefully be obtained.

Apart from pressure vessels there does not appear to be a general demand for stress relieving of welded constructions, but the replies from some countries indicated that stress relieving may be considered necessary to meet service conditions involving shock loading or fatigue loading. Welded tank cars, railway bogies, and certain welded constructions for naval use would appear to fall in this category.

Other rather special applications requiring stress relieving are welded vessels to hold certain corrosive media where welding stresses would facilitate local corrosion or stress-corrosion cracking, and structures where stability of dimensions within fine limits during machining or service is important.

Other Factors Determining when Stress Relieving is Mandatory

With parts such as boilers and other pressure vessels the replies indicated considerable difference in practice regarding the conditions, other than pressure, which determine when stress relieving is mandatory and when it may be omitted at the discretion of the manufacturer.

In some countries on the Continent of Europe, significance is attached to the weld-strength-factor, stress relieving being required when this exceeds 0·7 or 0·8. In U.S.A. and Britain, on the other hand, and also in Sweden, thickness of the plate is a determining factor. Other limiting factors employed by certain countries are the capacity of the vessel, the temperature of operation and the composition of the steel. Restraint of the weld is mentioned as a desirable factor and is implicit in British codes where the limiting thickness is a function of the diameter of the vessel.

Stress Relieving Conditions

It is generally agreed that where stress relieving is required the part should be heated in a furnace if possible, but induction heating and gas rings are mentioned by some correspondents, presumably where local stress-relieving has to be done, as for instance on butt welds in pipes.

The stress-relieving temperature range for carbon steel is generally accepted as 600-650 deg. C., but temperatures in the region of 900 deg. C. are sometimes used to bring about structural changes as well as to relieve stress, e.g. grain refinement of gas welds which normally have a coarser microstructure than electric welds. In Scandinavia low-temperature stress relieving at 200 deg. C. has been considered for large vessels that could not be heated to higher temperatures.

Advantage of Stress Relieving and Conditions Governing the Necessity for Stress Relieving

Whilst all the replies expressing definite views accepted the value of stress relieving for pressure vessels, there is clearly a lack of general conviction about this and a good deal of doubt as to the mechanism of any advantage resulting from stress relieving. Of the nine members, representing nine countries, replying to the Questionnaire, only four said "Yes" to the question "Do you personally think stress relieving is useful?" and only two of these gave increased safety in service as a reason for their view. It would appear that stress relieving is frequently applied merely because it is in the code of practice and because it enables manufacturers to use thinner plates and higher stresses without any conviction that the regulations are well founded. This seems to be a very unsatisfactory state of affairs. There should surely be general agreement that stress relieving is or is not useful for certain applications.

The different factors employed to determine when stress relieving is necessary (and therefore mandatory) in different countries are also indicative of a general lack of understanding of the real factors affecting the safety of welded pressure vessels and similar structures. Assuming stress relieving has some value we should surely aim at knowing which factors afford the best criteria of the conditions under which stress relieving is necessary. It seems hardly likely that such diverse factors as are employed in different countries can be equally useful as a guide. For example, "thickness" and "weld-strength-factor" (or stress) seem to be contradictory. This again is unsatisfactory. Furthermore, whatever factors are really appropriate, require to be evaluated quantitatively on a rational basis as the result of experiment and observation rather than arbitrarily as appears to be the case at present.

Whilst it is well known that attention is being given to some of these questions in several different countries, it is suggested that the Commission and its individual members should regard the clarification of these questions as of the highest practical importance and should encourage, whenever possible, work directed towards this end.

METAL-ARC WELDING OF ALUMINIUM-MAGNESIUM PLATE

Several years ago, the Association, anticipating a demand for the welding of thick aluminium alloy plate, initiated an investigation into the welding of heavy gauge medium-strength aluminium alloys by the metal-arc process. This was the only arc welding method available at that time.
This report has been prepared for "Welding Research" by P. T. Houldcroft, B.Sc., from the L.M.1 Committee document, "Interim Report on an Investigation of the Arc Welding of Thick Aluminium-5% Magnesium Alloy", by J. G. Ball and P. T. Houldcroft. The original report (L.M.1/11) was issued to Members of the Association in March 1949, and formed the basis of subsequent work which will be reported in future issues of "Welding Research."

INTRODUCTION

The investigation of the metal-arc welding of medium strength aluminium alloys was started by the examination of butt-welded joints in 1 in. thick aluminium-5 per cent. magnesium alloy. Welds in this material were prepared for the Association by several member firms and the examination of the welds and further supplementary tests were made in the Association's laboratories. It was hoped that an estimate of the quality of welds in thick aluminium-5 per cent. magnesium alloy plate, produced by the best available technique, could be made and that any special difficulties in metal-arc welding this material would be revealed.

The initial investigations were to be confined to the welding of 1 in. thick plate but the properties of these welds were lower than was expected and further tests were carried out on similar plate of ½ in. thickness. The welds in ½ in. thick material gave slightly higher strength properties and attention was then given to the factors which might cause these differences as well as to the reasons for the low strengths of metal-arc welds in these materials.

×2

Fig. 1. Porosity and flux inclusions in an eight-pass weld in ½ in. plate.

MATERIALS AND WELDING TECHNIQUE

All the tests reported were carried out on cold-rolled aluminium-5 per cent. magnesium alloy plate of approximately ½ in. and 1 in. (nominal) thicknesses. Analysis and mechanical properties of the plate material were as follows:

Analysis of Plate Material

Mg	4·7 per cent.
Mn	0·29 ,,
Fe	0·25 ,,
Si	0·13 ,,
Na and Ca	Present
Gas content	0·5 cc./100 gm.

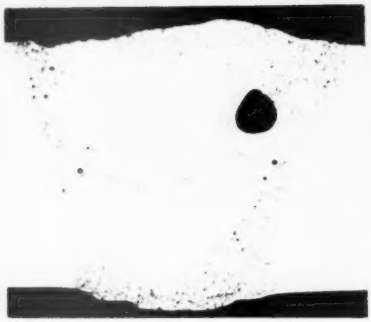
Mechanical Properties of Plate Material

	1 in. Plate as received	½ in. Plate	
		as received	annealed*
Ultimate tensile strength in tons per sq. in.	21·2	22·0	18·0
Elongation (per cent.)	10 (on 8 in.)	11-16 (on 2 in.)	27 (on 2 in.)

* After annealing for three-and-a-half hours at 380 deg. C.

Five types of electrodes were used with a variety of edge preparations. The first tests were made in ⅜ in. thick plate with 6 s.w.g. aluminium-5 per cent. magnesium electrodes. A 60° V was employed and eight passes were required with intermediate back chipping. The section in Fig. 1 is typical of the severe flux inclusions which resulted from this technique. Subsequent welds using the same electrodes were made with fewer passes and a moderate weaving technique, so that a larger weld pool was carried and the slag inclusions were reduced from the long string formation to the occasional rounded type shown in Fig. 2. With a larger weld pool the slag soldified less rapidly during electrode changes and there was less chance of slag being trapped at this point.

Other welds in ½ in. plate were made with 5/16 in. diameter electrodes using welding currents of up to 400 amps., and it was considered that an electrode of this size was desirable



×2

Fig. 2a. Unetched.

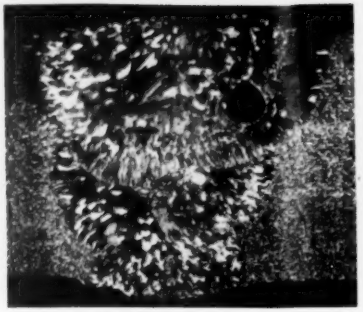


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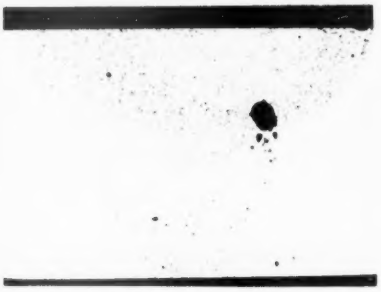
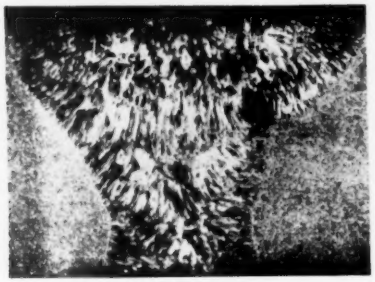
Fig. 2b. Etched.

Fig. 2. Plate and electrodes as for Fig. 1 but with improved welding technique.



×2

Fig. 3. Welded with larger electrodes (Unetched).

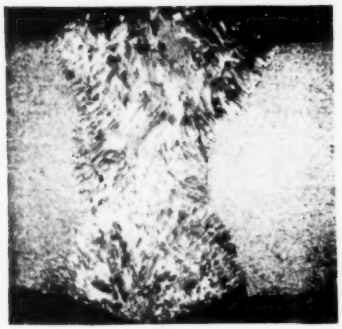


×2

Fig. 4. Same weld seam as in Fig. 3 but etched to show columnar crystals.

×2

Fig. 5a. Unetched.



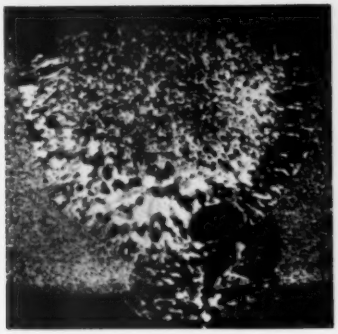
×2

Fig. 5b. Etched.

Fig. 5. Same welding conditions as in Fig. 4, but with double Vee preparation.

×2

Fig. 6a. Unetched.



×2

Fig. 6b. Etched.

Fig. 6. Single-pass top run with sealing run.
Prolonged heating due to low welding speed causing porosity to develop in the parent plate.

for plate of over ½ in. thickness as it reduced the risk of flux entrapment to a minimum (see Figs. 3, 4, 5 and 6). Preheating up to 250 deg. C. was necessary with all the welds in thick plate. When a large diameter electrode was used or a larger weld pool was carried it was found best to slightly tilt the plates being welded so that the slag ran away from the root. This was not necessary with plate thinner than about ½ in. or with electrodes of less than 4 s.w.g.

RESULTS

Mechanical Tests

The results of approximately forty tests indicated that values for the tensile strength of butt welds in the material employed, when an aluminium-5 per cent. magnesium filler wire or electrode was used, were approximately:

For gas welds in thin plate (¼ in. thickness)—13·5 tons per sq. in.

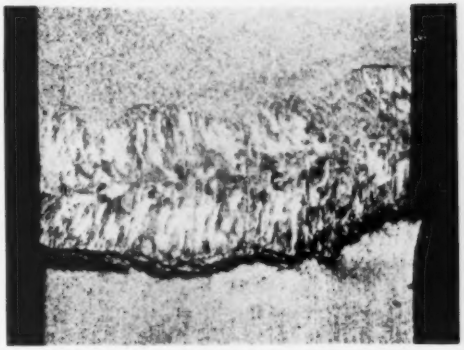
For arc welds in thin plate (¼ in. thickness)—11·0 tons per sq. in.

For arc welds in thick plate (⅜ in. thickness)—8·0 tons per sq. in.

Arc welds in ⅜ in. plate using an electrode with an aluminium-7 per cent. magnesium core wire gave tensile strengths of 9·5 tons per sq. in., but in the welds examined results above 11 tons per sq. in. for thin plate (¼ in.) were not obtained even when an aluminium-7 per cent. magnesium core wire was used.

The location of fracture in the welds in thick plate was usually in the weld metal, but in thin plate it was generally along the boundary of the weld metal. Fig. 7 shows this type of fracture. The multi-run welds examined, fractured first in the root of the weld, unless gross porosity of slag inclusions were present.

A number of welds were made with electrodes having different core wire composition from the parent plate. The highest strengths from an arc weld in thin plate were obtained with an aluminium-5 per cent. silicon electrode which gave a tensile strength of nearly 13 tons per sq. in. A gas weld also made in ¼ in. plate using an aluminium-5 per cent. silicon rod was found to have a tensile strength of only 10 tons per sq. in. An elongation of approximately 3 per cent. was observed in both of these tests; in the arc weld the deformation was mainly in the parent plate, but in the gas weld the weld metal itself was also deformed. Although arc welds using the high-silicon filler wire gave strengths approximately 1½ to 2 tons per sq. in. higher than welds made with an aluminium-magnesium filler wire, it was not suggested that the silicon containing wire would be suitable in practice because of the undesirable formation of the Mg_2-Si compound. The possibility of obtaining a satisfactory tensile strength by the use of an electrode with an Al-Mg-Si type core wire and a silicon content of less than 1 per cent. was considered. A single run weld in ¼ in. thick plate prepared with an 8 s.w.g. electrode containing 0·6 per cent. magnesium and 1·0 per cent. silicon had a tensile strength of approximately 11 tons per sq. in. Strengths of approximately 12 tons per sq. in. U.T.S. for welds in ¼ in. plate using an aluminium-1¼ per cent. manganese alloy electrode were reported, but severe weld cracking prevented the checking of this statement on samples supplied.



×3½

Fig. 7. Tensile test piece of weld in thin plate showing fusion-zone failure.

Examination of Microsections

Pin-hole porosity was a feature of all the welds which were examined, and slag inclusions were found in all multi-run welds, their presence being more marked in the welds with the highest number of runs. As it was known that moisture in the electrode coating was a source of porosity, attempts

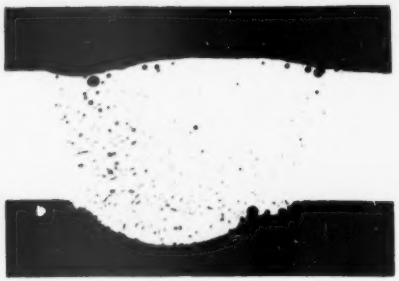


Fig. 8a. Unetched. ×3½

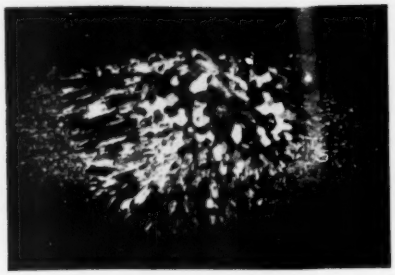


Fig. 8b. Etched. ×3½

Fig. 8. Single-pass weld in ¼ in. plate, showing elongated porosity due to low welding speed.

were made to reduce porosity by drying electrodes at over 500 deg. C. No noticeable improvement resulted from this high-temperature drying, as will be seen from the sections Fig. 2 where drying was carried out at 110 deg. C. to 150 deg. C. and Figs. 3 and 4 where the electrodes were heated to 500 deg. C.

Several welds were found to contain intercrystalline porosity which was elongated in the direction of solidification and associated with columnar crystal growth, as shown in Figs. 8, 9 and 10.

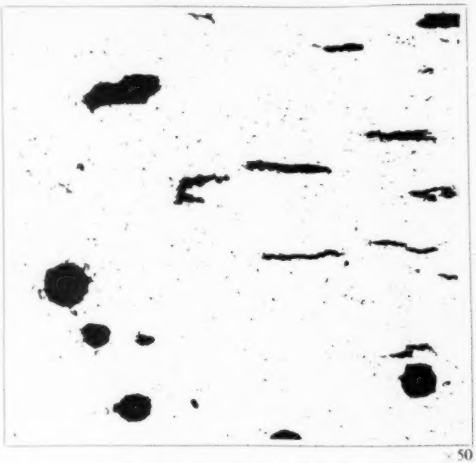
Surface blistering and porosity in the heat-affected zone, of the type sometimes associated with gas welds in the alloy investigated, were not observed in the arc welds unless the welding speed was low and the pre-heating temperature was abnormally high. Gas welds showed, however, that the material used was susceptible to these defects.

Analysis of Weld Metal

The weld metal deposited in these tests was analysed to determine magnesium loss and also to check the presence of trace elements.

Magnesium Content of Wire and Weld Metal

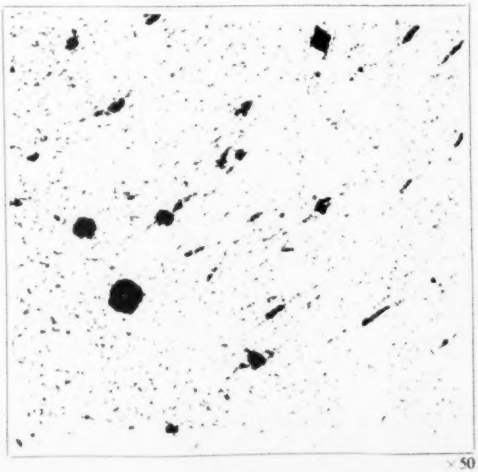
Core Wire (per cent.)	Weld Metal (per cent.)
(Nominal 5) 4·4	3·0-3·5
(Nominal 7) 6·5-7·0	4·5-5·0



×50

Fig. 9. Elongated porosity at the edge of a weld in ¼ in. plate. (Unetched.) See also Fig. 8a.

×10



×50

Fig. 10. Two examples, at different magnification, of elongated porosity in weld metal. See also Fig. 3.

It was found that at a magnesium loss of 20 to 30 per cent. of the magnesium present in the core wire occurred with both the 5 and 7 per cent. magnesium core wires.

At the time that these tests were made, it was thought that with the material employed and the high temperatures involved in arc welding, the oxide content of weld metal might be of importance. A number of oxide analyses were carried out, but the results seemed to indicate that the oxide present in slag inclusions was being included in the analysis. In view of this source of inaccuracy, no further oxide analyses were undertaken.

Oxide Content of Weld Metal

Code No.	Core Wire Type	Alumina (per cent.)	Magnesia (per cent.)
A	Al-5 per cent. Mg	0·34	0·08
B	Al-5 per cent. Mg	0·08	0·04
C	Al-7 per cent. Mg	0·07	0·03
D	Al-7 per cent. Mg	0·04	0·01
Parent plate material		0·011 Total	

Spectrographic analysis of the weld metal showed that both sodium and lithium were present in appreciable quantity. Typical results were:

Sodium and Lithium Analysis of Weld Metal

Core Wire Type	Na (per cent.)	Li (per cent.)
Al-5 per cent. Mg	0·02	0·05
Al-7 per cent. Mg	0·03	0·15

DISCUSSION OF RESULTS

Two types of porosity were observed in the welds: (*a*) generally distributed porosity in which the pores were rounded and of various sizes, and (*b*) elongated porosity associated with columnar crystals. The presence of porosity, particularly of the elongated type in multi-run welds, was undoubtedly responsible for a serious loss in strength, but it was difficult to assess the magnitude of this effect. Moisture in the electrode coating was known to be a cause of porosity in the weld metal, but evidently the drying of electrodes at over 500 deg. C. to remove as much moisture as possible, did not eliminate completely porosity in the weld. Therefore, the likelihood that some of the porosity may have originated from gas in the core wire could not be overlooked.

It was suggested that gas in the plate material might have been at least a contributory factor in the fusion-zone failure of arc welds in tensile testing. With low welding speeds and high pre-heating temperatures it had been observed that porosity developed adjacent to the weld in the same way as in a gas weld in this alloy. In a gas weld this defect may be observed in the heat-affected zone and extends over a considerable area. The more rapid heating and cooling of an arc weld causes such porosity to be located at the boundary of the weld metal, where it might cause premature failure in tensile testing.

The elongated porosity found in some of the welds examined was evidently injurious to the tensile strength, and it was suggested that such porosity might be more harmful in welds in thick plate, because of the different direction of solidification. As there was some degree of bottom cooling in the later stages of the multi-run butt welds in thick plate, some of the pores, which were elongated in the direction of solidification, were located so that when the welds were tested they lay across the direction of stressing. In the welds in thin plate, solidification proceeded to a greater extent from the sides of the weld, and in subsequent tensile testing any elongated porosity was longitudinal to the direction of stress and correspondingly less injurious to the mechanical properties.

Examples of elongated porosity are shown in Figs. 9 and 10. Welds in $\frac{1}{4}$ in. thick plate did not normally show elongated porosity (see Fig. 11), unless the welding speed was low, as in Fig. 8.

It was considered that these elongated pores were probably a result of gas, which occurred at the grain boundaries, due to the particular conditions of solidification and crystal structure encountered. Special electrodes with core wires containing grain refining elements were prepared so that the weld metal would have an equi-axed structure in which elongated porosity could not form. Titanium additions were particularly effective and prevented elongated porosity in weld metal, which had an exceptionally high gas content, as shown in Fig. 12 on next page.

The difference in tensile strength between welds in thick and thin plate led to a consideration of the effect of the number of runs deposited on the tensile strength of the joint. It was observed that there was a tendency for the fracture in tensile tests of multi-run welds to start at the root of the weld and this seemed to indicate that the earlier deposited runs were of lower strength.

In several multi-run welds in the first and second passes, fine cracks occurred which were not readily observed except in micro-sections (see Fig. 13). These cracks were obviously a cause of low strength, but it was also thought possible that the heating of the first runs by the later weld beads might have an adverse effect on mechanical properties.

A further possible cause of the higher strength of welds in thin plate was the method of edge preparation which affected the dilution of the filler metal by molten plate

Fig. 11a. Unetched. ×3½

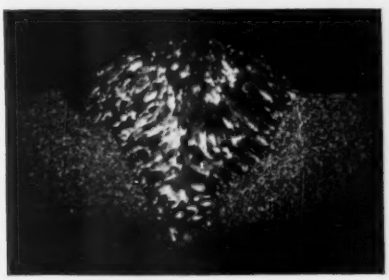


Fig. 11b. Etched. ×3½

Fig. 11. Single-pass weld in $\frac{1}{4}$ in. plate using high welding speed.

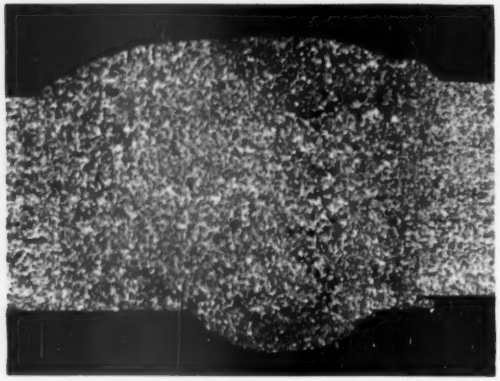
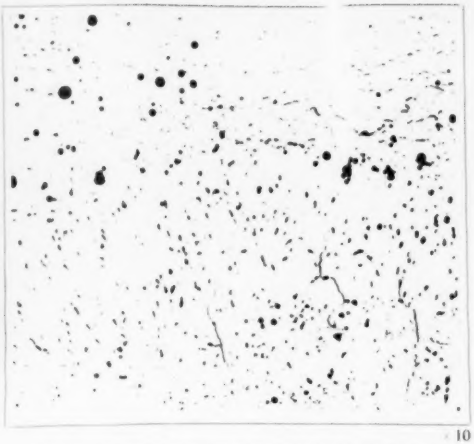


Fig. 12. Single-pass weld in ¼ in. plate using an electrode containing 0·5 per cent. titanium.



×10

Fig. 13. Elongated porosity and cracks in the 1st, 2nd and 3rd runs of a multi-run weld.

material. The welds in ¼ in. plate were made without edge preparation and using a small gap. This meant that the weld metal contained a high proportion of metal melted from the parent plate, which since it had not passed through the arc, might have had a higher potential strength than the filler metal itself.

It was considered that the presence of minor impurities, such as sodium and lithium, in the weld metal as a result of reactions between the filler metal and flux at high temperature might have been responsible for the generally low strength of metal-arc welds in the aluminium-magnesium alloys. Such minor impurities were thought to be more harmful with these alloys than other aluminium alloys. The presence of sodium in fluxes for melting certain of the aluminium magnesium alloys for casting purposes was already recognised as harmful, and it was suggested that sodium-free fluxes for welding might be an advantage. A few experiments were made at the time with sodium-free materials, but a successful weld bead could not be deposited.

CONCLUSION

The LM1/11 report showed that metal-arc welding of the aluminium 5-per cent. magnesium alloy plate with the electrodes which were then available could not be expected to give weld strengths of over 11 tons per sq. in. U.T.S. in thin material or over about 9 tons per sq. in. in plate of approximately 1 in. thickness.

Elongated porosity was shown to be a danger in certain circumstances and, titanium additions to the filler wire to prevent columnar crystal structure in the weld metal were considered an advantage. Core wires containing up to 0·2 per cent. titanium were used in all subsequent work.

It was also thought desirable that plate and core wires with a low gas content should be used in further work.

The presence in the weld metal of sodium and lithium was established and the possibility that these elements were responsible for the generally low strength of arc welds was considered.

FATIGUE TESTS ON DEFECTIVE BUTT WELDS

This report describes an exploratory investigation of the effect of certain weld defects on the fatigue strength of butt-welded mild steel plates. At the time when this work was put in hand by the Naval Construction Research Establishment, the same problem was under review by the Committee on Behaviour of Welded Structures under Dynamic Loading (F.E.8 Shipbuilding Panel) of the B.W.R.A. It was recognised that the exploratory tests would form a useful preliminary to the planning of a more extensive and long-term investigation by the Shipbuilding Panel, and the help given by the Admiralty in providing the test results is gratefully acknowledged. The need to pursue the long-term programme obviously remains, but these initial results are published since they add to the very limited data which are available on the effect of weld faults on fatigue strength and provide a basis for further consideration of the problem.

The report is published by permission of the Director of Naval Construction, Admiralty.

By W. G. WARREN, R.C.N.C.*

INTRODUCTION

Radiographic examination of welded joints in steel structures frequently reveals the existence of internal defects. Most of these fall into fairly well defined categories, for example, slag patches, parallel lines of slag, slag lines at root, lack of penetration, lack of side fusion, porosity, piping and cracking (normally, but not necessarily, associated with slag patches). Bad workmanship on the part of the welding operator is undoubtedly responsible for much of the defective work encountered, but in many cases factors beyond the control of the operator are involved. Cracking, porosity and piping may, for example, be entirely due to the chemical and physical properties of the plate being welded or the electrode employed, whilst the electrode may produce a tough slag difficult to free from inter-run crevices and so almost inevitably giving rise to slag inclusions.

Unsuitable design of structural details and a poor welding sequence may also be factors contributing to the production of defective welding.

An increase in knowledge of welding technology, together with an increased standard of work supervision, would be expected to lead to a reduction in the amount of defective welding, but it is evident that, at least in a manual welding process in which the human element is predominant, defects will never be completely eliminated from production shipwelding.

It is therefore highly desirable to know to what degree the defects affect the strength of the joint, so that in any particular case a decision may be made as to which defects must be repaired, and which may be tolerated.

Very little data exist, however, on which acceptance standards of weld quality may reliably be based. Tensile tests carried out at room temperature on sound and defective welded joints, frequently show no loss of strength in the defective specimens. Under other forms of loading, however, for example, fatigue, indication may be obtained of a reduction in joint strength.

A survey of the published results of fatigue tests carried out on welded joints of varying quality has been made by Weck.† The only defect which has been systematically investigated to determine the effect of varying severity on the fatigue strength is weld porosity; in this investigation, photometry was used to provide a direct means of measuring defect severity. The results of all fatigue tests on defective welded joints are characterised by considerable scatter. Porosity, composed largely of approximately spherical voids might be expected to yield more uniform results, but in the investigation referred to a scatter of the order of 30 per cent. was experienced.

Among the many difficulties involved in attempting to assess the effects of internal defects upon the fatigue strength of a welded joint are the following:

(*a*) There is no non-destructive testing method which will reveal all internal defects present in a weld in such a manner as to enable the severity of each to be defined, even arbitrarily.

X-radiography has the advantage of yielding a photograph, from which the defects may be classified according to the arbitrary definitions evolved from scrutiny of radiographs of production welding, but it is limited to the detection of defects lying sensibly in the plane of the rays and of greater

* Naval Construction Research Establishment, Dunfermline.

† R. Weck, *The Welder*, **19**, Nos. 104 and 105.

than a certain minimum width (measured perpendicularly to the plane of the rays). For example, it will not reveal micro-cracking in the heat-affected zones of a joint, and fatigue failure might well be initiated at such a defect.

(*b*) The acuity of a notch perpendicular to the direction of loading is known to exercise an important effect on fatigue strength. Even though, on careful scrutiny, two radiographs may appear to contain defects (say, slag patches) of similar severity, it is quite possible that the sharpness of edge of one may considerably exceed that of the other. In the case of weld cracks, however, it is probable that the sharpness is sensibly constant. The results of tests on such specimens do, in fact, show less scatter and a curve of stress against a number of reversals to failure has been obtained.

The investigation was originally planned to be of an exploratory character, to discover whether useful results could be obtained from tests at a fixed stress range of ± 8 tons per sq. in. The advantage of such a procedure is that, in a series of tests in which scattered results are anticipated, a *criterion of performance* may be obtained with fewer specimens than would be required to produce a full S-*n* curve. Where considered possible, however, S-*n* curves have been obtained.

MATERIAL

The plates were of $\frac{1}{2}$ in. thick, ship quality mild steel, and the electrodes employed for the manually welded specimens were to B.S. Classification R.317, and were of one brand.

The edge preparation for welding was the usual single Vee 60 deg. included angle with $\frac{1}{8}$ in. root face and gap. The surfaces of the plates were moderately corroded, but not to a degree beyond that commonly accepted in shipbuilding. No attempts were made to improve the surface condition as it was considered that the weld defects would influence the strength more than would the surface pitting.

The specimens were generally 2 ft. 6 in. long by 6 in. wide, with the butt weld transverse at mid-length, the "crack" series and the submerged-arc welded specimens being of a reduced size (see Fig. 1 (*a*) and (*b*)). The cracks were produced by depositing a small root run under highly restrained conditions and welding over to complete the joint before the crack forming in the root weld had propagated to its surface. Fig. 19 shows the type of crack obtained by this procedure. After radiographic examination, the specimens were cut from the welded plates, with the crack at mid-length of the weld. The submerged-arc specimens with lack of penetration were welded with one run from each side at 500 amps.

To reduce to a minimum the degree of eccentric loading of the weld, the procedure illustrated in Fig. 2 (*a*) and (*b*) was adopted by which means it was possible to *straighten* the test piece without straining the weld. The final form of the specimen was such that the ends to be held in the grips were flat and their centre lines passed through the centre line of the weld.

Before testing, the reinforcement was removed so that the weld surface was flush with the plate. The radiographic technique embodied the use of Ilford "C" films in lead screens, developed under standard conditions, viz. seven minutes at 68 deg. F.

TEST DETAILS

All tests were carried out with "push-pull" loading, i.e. the loading cycle alternated between tension and compression of equal value. The 30 by 6 in. specimens were loaded to ± 8 tons per sq. in. in a Losenhausen pulsator at a frequency of 400 cycles per minute, the number of cycles to fracture being recorded (see Table). Strain readings were taken at the four corners of the weld by Huggenburger tensometers. The variation of strain measured by these gauges was

Fig. 1a. Tests 1-26. (*A* = 30 *in.*, *B* = 6 *in.*)

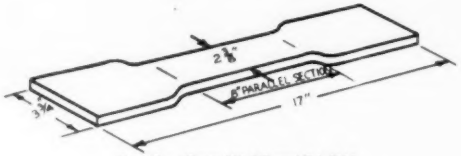


Fig. 1b. Tests U1-U7 and R1-R18.

Fig. 1. Dimensions of test specimens.

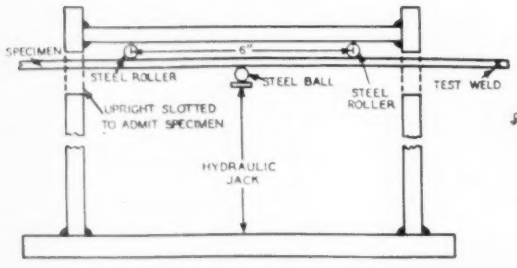


Fig. 2a. Diagram of straightening jig.

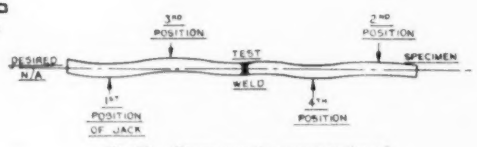


Fig. 2b. Diagrammatic representation of straightening method.

Fig. 2. Method of straightening specimens.

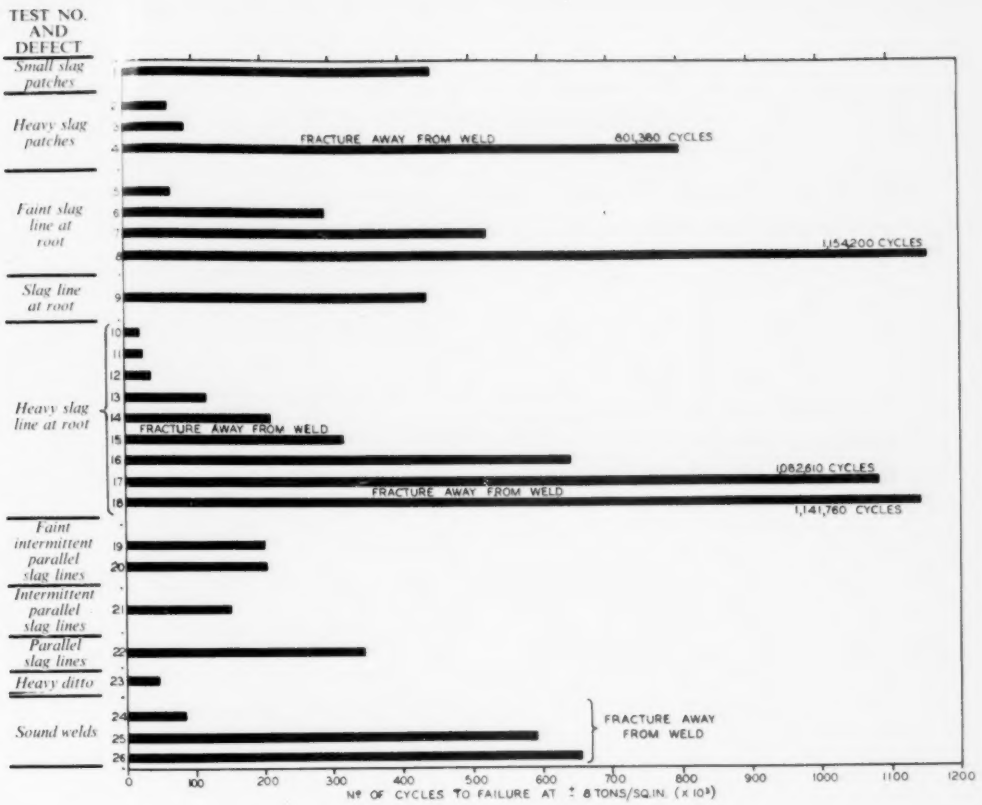

TEST NO. AND DEFECT
Small slag patches
Heavy slag patches
Faint slag line at root
Slag line at root
Heavy slag line at root
Faint intermittent parallel slag lines
Intermittent parallel slag lines
Parallel slag lines
Heavy ditto
Sound welds
FRACTURE AWAY FROM WELD
801,380 CYCLES
1,154200 CYCLES
FRACTURE AWAY FROM WELD
1082610 CYCLES
FRACTURE AWAY FROM WELD
1,141,760 CYCLES
FRACTURE AWAY FROM WELD
0 100 200 300 400 500 600 700 800 900 1000 1100 1200
Nº OF CYCLES TO FAILURE AT ± 8 TONS/SQ.IN. (x 10³)

Fig. 3. Diagrammatic representation of fatigue life of test specimens 1-26.

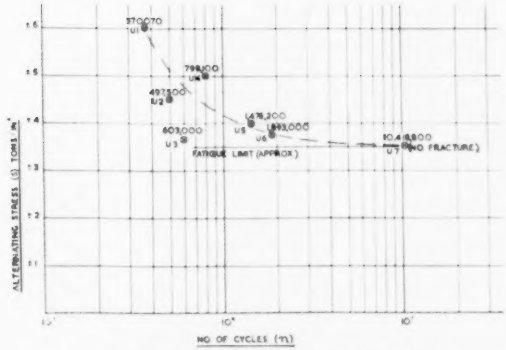


Fig. 4. S-*n* curve for specimens with lack of penetration (U1-U7).

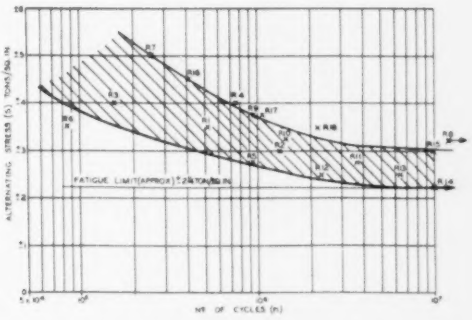


Fig. 5. S-*n* curves for specimens with fine longitudinal cracks (R1-R18).

generally well within 5 per cent. of the mean, thus indicating satisfactory axiality of loading.

Both the submerged-arc welded specimens (Ref. U) and the "crack" series (Ref. R) were tested in an Avery-Schenck 20 tons machine at a varying frequency, dependent on load, of about 2,500 cycles per minute.

RESULTS OF TEST

Figs. 6-18 show X-radiographs, taken before testing for a selection of the specimens, together with the corresponding fractured surfaces. The fatigue life of specimens 1-26 are shown in Fig. 3, in the form of a block diagram, specimens being grouped according to the internal defect and its severity as defined by the standard terms laid down by the Radiography Section D.N.C., Admiralty. S-*n* curves for the specimens with lack of penetration and cracks are given in Figs. 4 and 5 respectively.

Table

Specimen No.	Defects	Stress Range (tons per sq. in.)	No. of Cycles to Failure
1	Small patches of slag	±8·0	446,480
2	Heavy slag patch	±8·0	62,810
3	" " "	±8·2	85,660
4	" " "	±8·1	801,380*
5	Faint slag line at root	±8·0	46,470
6	" " " "	±8·0	290,290
7	" " " "	±8·0	526,010
8	" " " "	±8·1	1,154,200
9	Slag line at root	±8·0	437,950
10	Heavy slag line at root	±8·2	21,580
11	" " " "	±8·0	24,370
12	" " " "	±8·2	36,600
13	" " " "	±8·2	115,280
14	" " " "	±8·0	211,390
15	" " " "	±8·1	318,370*
16	" " " "	±8·0	641,920
17	" " " "	±8·0	1,082,610
18	" " " "	±8·1	1,141,760*
19	Faint intermittent slag lines	±8·0	152,030
20	" " "	±8·0	526,101
21	Intermittent parallel slag lines	±8·0	121,070
22	Parallel slag lines	±8·0	347,570
23	Heavy parallel slag lines	±7·9	49,370
24	Sound weld	±8·0	49,370*
25	" "	±8·0	495,160*
26	" "	±8·0	650,750*
R 1		±3·5	521,400
R 2		±3·0	1,387,600
R 3		±4·0	160,190
R 4		±4·0	767,300
R 5		±2·75	939,500
R 6		±3·5	85,600
R 7		±5·0	250,000
R 8		±3·25	12,239,100
R 9	Fine longitudinal cracks	±3·75	963,300
R 10		±3·25	1,492,700
R 11		±2·75	3,694,000
R 12		±2·5	2,291,700
R 13		±2·5	6,388,200
R 14		±2·25	No failure at 10^7
R 15		±3·0	9,800,000
R 16		±4·5	4,121,700
R 17		±3·75	1,070,600
R 18		±3·5	2,221,200
U 1		±6·0	370,070
U 2		±4·5	497,500
U 3		±3·65	603,000
U 4	Continuous lack of penetration	±5·0	798,100
U 5		±4·0	1,476,200
U 6		±3·75	1,893,000
U 7		±3·5	No failure at 10^7

* Fracture in plate away from weld.

DISCUSSION

The results given in Fig. 3 show such considerable scatter that it is not considered possible to draw firm conclusions regarding relative severity of the various defects. Of the various defects investigated, most attention was paid to that involving a heavy line of slag at the root. The limits of performance of the nine specimens forming this group were 21,580 for specimen No. 10 to a figure in excess of 1,141,760 for specimen No. 18.

The three specimens containing welds whose radiographs showed freedom from defect, all fractured away from the weld, as did specimens whose welds contained a heavy slag patch and a heavy slag line at root respectively; these fractures were all associated with imperfections in the surface condition of the plates. The average endurance of those specimens which fractured in the plate is approximately 650,000 cycles, and it is, therefore, evident that the fatigue strength of such plate, unwelded, would be appreciably below ±8 tons per sq. in.

The "heavy slag patch" and "heavy line at root" specimens produce the greatest losses in strength, but each of these groups contains a specimen in which fracture occurred in the plate, at 801,380 and 1,141,760 cycles respectively.

There appears to be rather more consistency among the "parallel lines of slag" group with endurances tending to vary in accordance with defect severity. It is noted that the classification "faint intermittent" parallel slag lines, a very common defect, not easily avoided in practice, leads to an appreciable loss in strength.

The fatigue strength of the submerged-arc welds with lack of penetration, is seen from Fig. 4 to be approximately ±3½ tons per sq. in. The use of an automatic welding process for these specimens had the advantage of producing more uniform penetration than would be achieved by manual welding; it is, however, probable that, due to the superior properties of the submerged-arc deposit, a manually welded set of specimens, in otherwise the same condition, would have a slightly lower fatigue strength. Tests on the "crack" series of specimens (see Fig. 5) give a fatigue strength of ±2¼ tons per sq. in.

If the S-*n* curves of Figs. 4 and 5 are roughly extrapolated to determine endurance at ±8 tons per sq. in., and figures obtained are compared with those given in Fig. 3, it appears reasonable to conclude that, as would be expected, cracks and lack of penetration are the most serious defects of the types examined. In comparing the fatigue strengths arrived at, it is to be noted that the stresses given are *nominal* in that they are based on the gross sectional area of specimen. If allowance is made for the local reduction in area at the weld due to the defect, the fatigue strengths would be increased by approximately 20 per cent. and 10 per cent. in the case of lack of penetration and cracks respectively. The fatigue strengths would then become ±4¼ tons per sq. in. and ±2½ tons per sq. in.

CONCLUSIONS

The results of the "endurance at ±8 tons per sq. in." tests are characterised by such extensive scatter that it is not considered possible to determine from them the relative severity of the defects investigated; only in the case of "parallel lines of slag" does there appear to be anything approaching reasonable consistency. The S-*n* curves drawn for the "cracks" and "lack of penetration" specimens show, however, that in these cases reasonably firm fatigue limits may be determined. The conclusion which may, therefore, be drawn is that it is possible to correlate the performance under fatigue loading of a welded joint containing internal flaws, with the appearance of its radiograph, when the flaw has the nature of a crack or lack of penetration, but not a slag inclusion. It is suggested that the reason for this is the

more uniform stress concentration effect to be expected at the edges of cracks and lack of penetration, compared with the more irregular edges of slag inclusions.

Cracks and lack of penetration are seen to be the most serious of the defects tested. The former give a fatigue strength of $\pm 2\frac{1}{2}$ tons per sq. in. and the latter $\pm 4\frac{1}{2}$ tons per sq. in., after an approximate allowance is made in each case for loss of sectional area due to the defect.

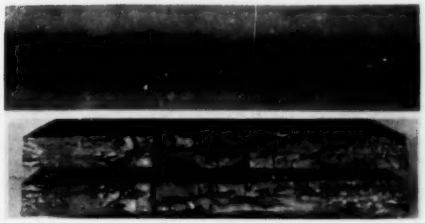


Fig. 6. X-radiograph and fracture surfaces of specimen 1, showing small patches of slag. *Fatigue life* 446,480 *cycles at* $\pm 8{\cdot}0$ *tons per sq.in.*

Fig. 7. Specimen 2, showing heavy slag patches. *Fatigue life* 62,810, *cycles at* $\pm 8{\cdot}0$ *tons per sq.in.*

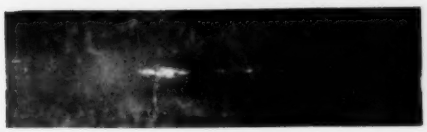


Fig. 8. X-radiograph of specimen 4, which fractured away from the weld. *Fatigue life* 801,380 *cycles at* 8·1 *tons per sq.in.*

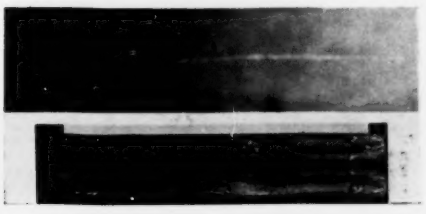


Fig. 9 *(left).* Specimen 7, showing faint slag line at root. *Fatigue life* 526, 010 *cycles at* $\pm 8{\cdot}0$ *tons per sq.in.*

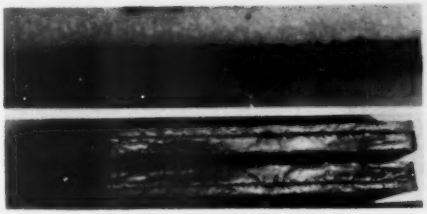


Fig. 10. Specimen 9, showing slag line at root. *Fatigue life* 437,950 *cycles at* $\pm 8{\cdot}0$ *tons per sq.in.*

Fig. 11. Specimen 12, showing heavy slag line at root. *Fatigue life* 36,600 *cycles at* $\pm 8{\cdot}2$ *tons per sq.in.*

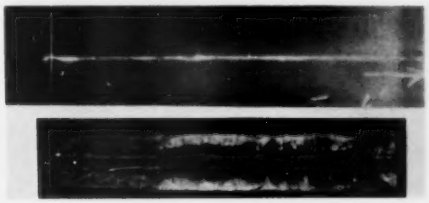


Fig. 12. Specimen 14, showing heavy slag line at root. *Fatigue life* 211,390 *cycles at* $\pm 8{\cdot}0$ *tons per sq.in.*

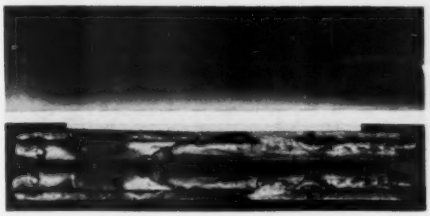


Fig. 13. Specimen 17, showing heavy slag line at root. *Fatigue life* 1,082,610 *cycles at* $\pm 8{\cdot}0$ *tons per sq.in.*

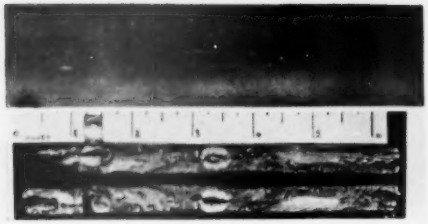


Fig. 14. Specimen 19, showing faint intermittent slag lines. *Fatigue life* 152,030 *cycles at* ±8·0 *tons per sq.in.*

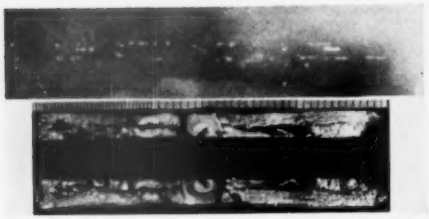


Fig. 15. Specimen 21, showing intermittent slag lines. *Fatigue life* 121,070 *cycles at* ±8·0 *tons per sq.in.*

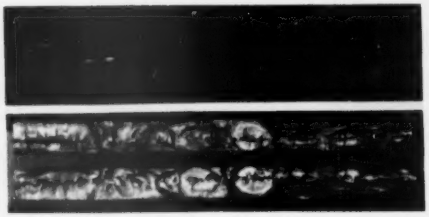


Fig. 16. Specimen 22, showing parallel slag lines. *Fatigue life* 347,570 *cycles at* ±8·0 *tons per sq.in.*

Fig. 17. Specimen 23, showing heavy parallel slag lines. *Fatigue life* 49,370 *cycles at* ±7·9 *tons per sq.in.*

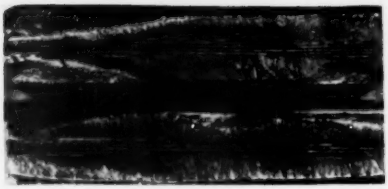


Fig. 18. Typical submerged-arc welded specimen with continuous lack of penetration.

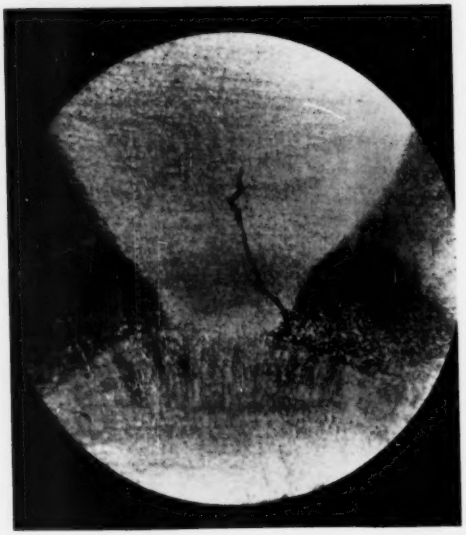


Fig. 19. Typical manually welded specimen showing fine crack. Macrograph of crack ×8.

RESISTANCE WELDING OF COLD-HEADED BOLTS

The work described in this report was carried out by the B.W.R.A. under the guidance of the FR.3 Committee on the Projection Welding of Steels, with the object of developing standard bolt head designs which could be produced by the cold-heading process, and used for welding to sheet material.

By J. E. ROBERTS, M.Eng., A.I.M.

SYNOPSIS

The development of a design of bolt head for projection welding to sheet material (from 12 s.w.g. to 20 s.w.g.) is described. Considerable use has been made of statistical techniques in the experimental work, for comparing the effects of the factors involved in welding, especially of bolt-head contour. The work has enabled provisional standard bolt head designs to be fixed for 5/16 in. diameter, 0 B.A. and 2 B.A. sizes, for production by cold heading. Such bolts have been used in electrode life tests, and over 6,000 welds were made without any deterioration in weld strength or consistency, and without the need to dress the electrodes.

It is concluded that bolts made to the provisional design can be used with confidence on long production runs.

INTRODUCTION

The advantages of the resistance welding method for attaching bolts to sheet, are the low cost of production of such bolts, and that attachment on mass-produced parts by automatic machines is cheap, rapid and accurately controlled. A present disadvantage is that the method is suitable only when the job can be brought to the welding machine.

The results of the research work have enabled standards to be laid down for bolts of 5/16 in. shank and 0 and 2 B.A. sizes, with recommended conditions for attaching these sizes to sheet from 12 to 20 s.w.g. thickness. The statistical terms used in the presentation of the experimental results are briefly explained in the appendix to the report.

MATERIALS AND MACHINES

The sheet material used in the tests was all to specification S. 84, i.e. a deep-drawing quality steel, the actual analysis of which was as follows:

	20 s.w.g. Sheet (per cent.)	12 s.w.g. Sheet (per cent.)
Carbon	0·040	0·050
Manganese	0·350	0·280
Sulphur	0·014	0·017
Phosphorus	0·016	0·015
Nickel	0·039	0·047
Chromium	0·003	0·002
Copper	0·010	0·040
Tin	0·005	0·012
Molybdenum	0·004	0·006

The bolts used in the preliminary work and the provisional standard bolts were all of normal wire, as used by the bolt manufacturers, the compositions of which were:

	5/16 in. (per cent.)	0 B.A. (per cent.)	2 B.A. (per cent.)
Carbon	0·15	0·10	0·09
Silicon	0·03	0·04	0·01
Manganese	0·50	0·45	0·45
Sulphur	0·054	0·035	0·046
Phosphorus	0·033	0·021	0·017

All material was free from rust and scale.

The welding machines used were a 100 kVA projection welder fitted with thyratron timer and ignitron contactors for the 5/16 in. size bolts, and a 25 kVA spot welder fitted with thyratron timer and electro-mechanical contactor for the 0 and 2 B.A. sizes. The timers of both machines were carefully checked to ensure that the correct current durations would be obtained.

The electrodes in all cases were faced with tungsten copper and internally water-cooled. This arrangement was found to give excellent electrode life, over 6,000 welds being made with no necessity for trimming.

METHOD OF INVESTIGATION AND RESULTS

The investigation was carried out in several well-defined stages as follows:

1. Determination of suitable heads for 5/16 in. diameter bolts using 12 s.w.g. sheet.
2. Tests on 0 B.A. and 2 B.A. bolts with 12 s.w.g. sheet using head design suggested by item 1.
3. Tests on 20 s.w.g. sheet with recommended bolts of 5/16 in. 0 B.A. and 2 B.A. shank diameter.
4. Life tests using recommended standard bolt heads.

5/16 in. diameter Bolts to 12 s.w.g. Sheet

Determination of Optimum Head Radius and Welding Condition for Hexagon Headed Bolts.—The major investigation used 5/16 in. cold-headed bolts. Normal hexagon head bolts were obtained and the heads machined to give a domed head, four different radii (1*d*, 2*d*, 4*d* and 8*d*, where *d* is the diameter of the shank) being used. The underside of the head was also trimmed to remove burrs left from forming the hexagon on the head.

With each of these radii a series of welds was made, using four values of electrode load for each head, and a range of current and time which covered all practicable possibilities, i.e. upper limit determined by tendency to splash, or exceeding 70 cycles duration, and the lower limit by the obvious low strength weld produced. Convenient intervals between the extremes were used, and three welds made at each selected condition. These welds were then tested in

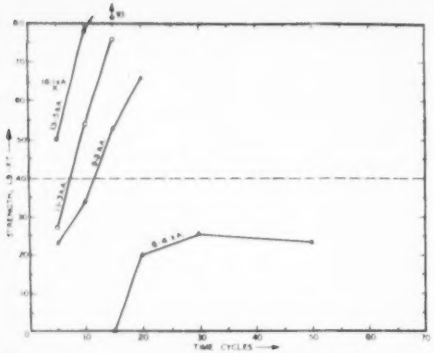


Fig. 1. Bolt welds with 5/16 in. dia. shank, 0·625 in. radius head, at 1,250 lb. load.

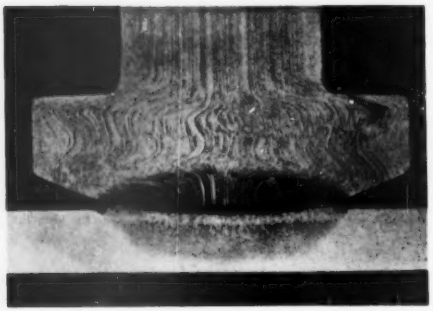


Fig. 2a Photomacrograph of bolt weld of pressure weld type.

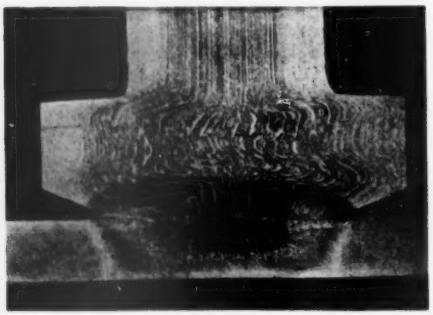


Fig. 2b. Photomacrograph of bolt weld of fused weld type.

torsion, using a torque spanner with special adaptors, and the strengths plotted to give curves of strength against time for each current used. A typical curve is shown in Fig. 1. The values of current were obtained by recording the integrated output of an air-cored toroid, linked with the secondary circuit, on a cathode ray oscillograph. This method has been fully described elsewhere[1, 2].

The curves so obtained were used to select conditions suitable for more detailed study, and a further series of welds were made. The basis of selection was a torsion strength of not less than 40 lb.-ft., and not more than 70 lb.-ft. (the bolt shank torsion strength was 33 lb.-ft.).

At each condition selected, eleven specimens were welded, 10 of which were tested in torsion and one sectioned for metallurgical examination. The actual order in which the conditions were used was determined randomly to eliminate the effect of any systematic variations in the machine, e.g. mains voltage fluctuations, etc. The results were subjected to statistical analyses, i.e. the variance, standard deviation and coefficient of variation were determined and compared. A summary of the results is contained in Table I.

The average variances for the different head radii were calculated and compared and show that the head radius of 0·625 in. gave most consistent results over the widest range of conditions, and this radius was therefore selected as the standard to be used in future work. A reduction in electrode load caused a slight drop in strength with no effect on consistency. The 1250 lb. load was selected, as variations from it would have little effect on weld strength, and the intermediate value of current (11·3 kA) used with the load was also selected as most suitable.

The metallurgical examination showed that the weld structure may contain a fused nugget, or may be a pressure weld, i.e. formed in the solid phase, with no fused nugget. Examples are shown in Fig. 2. In order to determine whether either structure was advantageous, further tests were carried out, with static testing, impact testing by a modified Izod test, and also by a special impact torsion test.[3] None of these tests showed any difference between the types of weld, so that mean strength and consistency of strength were used as the main criteria in selecting recommended conditions.

Determination of Optimum Head Land.—All the above tests were made with a hexagon head for convenience in torsion testing, but the most suitable head for use in practice

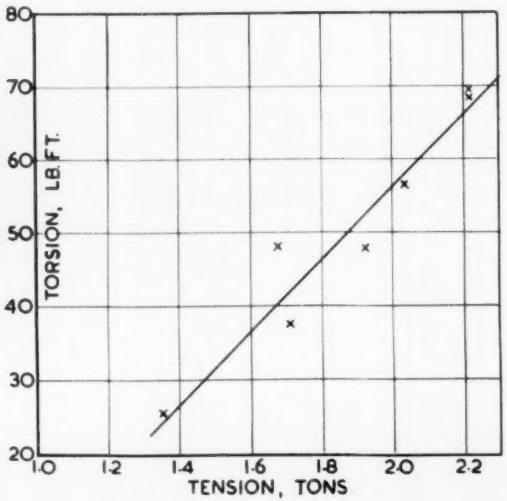


Fig. 3 (*right*). Relationship of tensile and torsional strengths for 5/16 in. bolts welded to 12 s.w.g. sheet.

Table I. – Torsion Strengths of Joint for 5/16 in. Bolts Welded to 12 s.w.g. Sheet

Head Radius (ins.)	Electrode Load (lb.)	Welding Current (kA)	Weld Time (Cycles 50 c/s)	Torsion Strength (lb.-ft.)	Variance	Coefficient of Variation
0·3125	1000	13·5	10	60	5·96	4·1
		11·6	15	64	4·46	3·3
		9·3	20	56	3·43	3·3
		6·4	40	57	52·05	12·8
	1250	13·5	8	54	11·82	6·3
		11·6	10	59	1·82	2·3
		9·3	20	63	5·51	3·7
		6·4	30	55	10·96	6·0
	1500	13·5	8	63	3·56	3·0
		11·6	10	66	2·17	2·2
		9·3	20	69	1·61	1·9
		6·4	30	52	3·51	3·6
	1750	13·5	5	61	2·93	2·8
		11·6	10	67	5·96	3·7
		9·3	20	73	7·82	3·9
		6·4	40	75	11·43	4·5
0·625	1000	13·5	5	47	4·25	4·4
		11·3	10	48	3·47	3·9
		9·3	15	51	3·89	3·9
	1250	13·5	5	51	14·37	7·5
		11·3	10	58	7·63	4·7
		9·3	15	49	5·37	4·7
	1500	13·5	5	50	4·36	4·2
		11·3	10	60	11·74	5·7
		9·3	15	55	8·05	5·2
	1750	16·1	5	67	6·26	3·7
		13·5	5	61	1·53	2·0
		11·3	10	62	7·63	4·4
		9·3	15	55	6·16	4·5
1·25	1000	16·1	5	51	5·12	4·5
		13·5	5	38	3·82	5·1
		11·6	10	42	2·04	3·4
		9·3	20	40	2·40	3·9
		6·4	40	38	7·29	7·1
	1250	16·1	5	61	1·34	1·9
		13·5	8	54	5·17	4·3
		11·6	10	49	34·22	11·9
		9·3	20	45	2·54	3·5
		6·4	50	45	5·29	5·1
	1500	16·1	5	59	4·46	3·6
		13·5	8	57	5·60	4·2
		11·6	15	61	1·73	2·2
		9·3	40	63	7·60	4·3
		6·4	70	42	6·27	5·9
	1750	16·1	5	65	4·01	3·1
		13·5	5	48	20·68	9·5
		11·6	10	49	8·27	5·9
		9·3	30	48	13·16	7·5
		6·4	70	59	30·54	9·4
2·50	1000	16·1	5	47	6·04	5·4
		13·5	8	44	26·32	11·7
		11·6	10	41	11·57	8·4
		9·3	25	40	2·48	4·0
		6·4	60	34	24·89	14·7
	1250	16·1	5	53	7·79	5·2
		13·5	8	52	8·67	5·7
		11·6	10	44	9·16	6·8
		9·3	30	52	4·84	4·3
		6·4	70	42	31·38	13·2
	1500	16·1	5	55	8·18	5·2
		13·5	8	57	6·44	4·5
		11·6	20	62	9·29	4·9
		9·3	40	56	8·77	5·3
		6·4	70	40	10·04	7·8
	1750	16·1	5	56	13·36	6·6
		13·5	10	73	4·22	2·8
		11·6	20	54	1·82	2·5
		9·3	50	59	33·07	9·7
		6·4	70	50	15·56	7·9

was required to be circular and as small as possible. A series of welds was therefore made to establish relationship between tension and torsion strengths, and this relationship is shown by the graph of Fig. 3. A further series of welds was then made, using heads of three different diameters—$\frac{1}{4}$ in., 7/16 in., and $\frac{3}{8}$ in.—all having a dome radius of 0·625 in., with a range of welding conditions. The results are shown in Table II.

The smallest size was not satisfactory as electrode wear was extremely rapid and a somewhat lower strength was obtained. The two larger sizes gave practically the same results, and as a small head is desirable, 7/16 in. diameter was selected as standard.

Tests on 0 B.A. and 2 B.A. Bolts (12 s.w.g. Sheet).

A similar sequence was used for 0 and 2 B.A. sizes, but on the basis of the experience gained with the 5/16 in. bolts, modifications in the tests for welding these sizes to 12 s.w.g. sheet were as follows:

(1) Only one relationship of head radius and shank diameter, i.e. $r = 2d$, was used. This gave radii of 0·472 in. for 0 B.A. and 0·370 in. for 2 B.A.

(2) After selection of suitable conditions, only one head diameter was used, that which gave a land of 1/16 in. The resulting diameters were 0·361 in. for 0 B.A. and 0·310 in. for 2 B.A.

(3) No relationship between tension and torsion strengths was obtained, since it was found that if the torsion strength was adequate, tension testing resulted in failure of the bolt shank. Additionally, torsion testing was satisfactory even with round heads, for these two smaller sizes, and therefore was used in the life series.

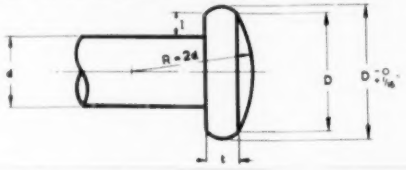
The minimum acceptable torsion strengths were fixed as 17·5 lb.-ft. for 0 B.A. (bolt strength 14 lb.-ft.) and 10 lb.-ft. for 2 B.A. (bolt strength 7 lb.-ft.), though for particular applications higher strengths may be needed and the results of the main consistency series are given in Tables III and IV for 0 and 2 B.A. respectively.

For 0 B.A. bolts the high and low currents give a poorer consistency than the intermediate values; electrode load has practically no effect on consistency or strength, and therefore the intermediate value is selected as most useful, since any accidental variations from it will have negligible effect on the weld.

Similarly, for the 2 B.A. size, load has no effect and changes of current still produce welds of excellent consistency. The intermediate values are therefore again chosen as most suitable.

Welding of Bolts to 20 s.w.g. Sheet

A tentative standard head was adopted for tests on 20 s.w.g. sheet, i.e. head radius (R) = 2 × shank diameter, head land = 1/16 in. and head thickness 1/16 in. for 5/16 in. 0 B.A. and 2 B.A. sizes (Fig. 4). Conditions investigated were suggested by the previous work on 12 s.w.g. plate and the results obtained are given in Table V. These results confirmed the high quality of the welds and the suitability of the selected welding conditions. In general, electrode loads must be reduced in welding 20 s.w.g. sheet to avoid dimpling of the flat electrode in contact with the sheet.



Size	Shank Diameter *d*	Head Radius R	Diameter across Flat under Head D	Width of Land *l* (min.)	Thickness of Head *t* (min.)
5/16 in.	0·3125	0·625	0·4375	0·0625	0·0625
0 B.A.	0·236	0·472	0·361	0·0625	0·0625
2 B.A.	0·185	0·370	0·310	0·0625	0·0625

Fig. 4. Provisional standard head design of cold-headed bolts.

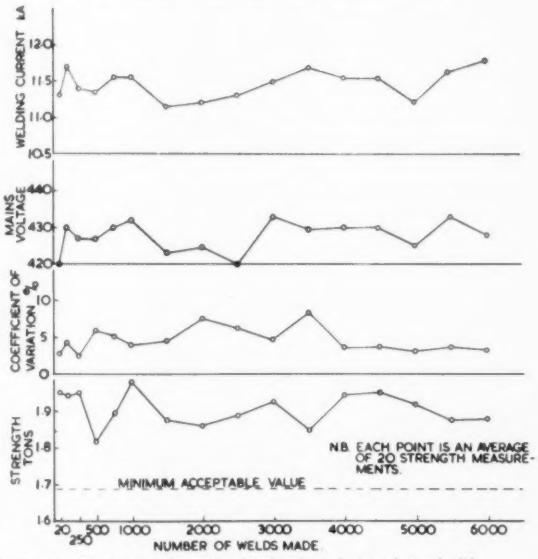


Fig. 5. Weld strengths and related values during electrode life tests for welding 5/16 in. diameter bolts to 12 s.w.g. sheet.

Table II. Welding Conditions and Results for Welding of 5/16 in. Bolts with Circular Head

Electrode Load (lb.)	Welding Current (kA)	Weld Time (Cycles 50 c/s)	Head Diameter (ins.)	Mean Strength (tons)	Coefficient of Variation	Remarks
1250	14·8	5	$\frac{1}{4}$	1·80	2·77	Some splash
	14·2	5	7/16	1·76	1·68	,, ,,
	13·6	5	$\frac{3}{8}$	1·73	3·86	Quite a lot of splash
1250	12·0	10	$\frac{1}{4}$	1·98	2·57	—
	11·5	10	7/16	2·00	4·00	—
	11·0	10	$\frac{3}{8}$	1·91	6·68	Splash
1250	9·8	15	$\frac{1}{4}$	2·08	4·01	—
	9·6	15	7/16	2·02	0·12	—
	9·0	15	$\frac{3}{8}$	1·96	6·21	—

Table III.—Torsion Strengths of Joint for 0 B.A. Bolts 0·472 in. Head Radius, Welded to 12 s.w.g. Sheet

Electrode Load (lb.)	Current (kA)	Weld Time (Cycles, 50 c/s)	Torsion Strength (lb.-ft.)	Variance	Coefficient of Variation
300	7·2	10	24	2·77	6·9
	6·4	15	25	1·07	4·2
	5·2	20	20	0·84	4·6
	4·3	40	19	1·43	6·3
500	7·2	10	24	2·89	7·1
	6·3	10	19	0·49	3·8
	5·2	20	20	0·62	4·0
	4·2	40	15	1·29	7·5
670	7·7	10	25	0·94	3·8
	6·5	10	19	0·68	4·3
	5·4	15	17	1·29	6·7
	4·4	50	16	1·29	7·2

Table IV.—Strengths of Joint for 2 B.A. Bolts, 0·370 in. Head Radius, Welded to 12 s.w.g. Sheet

Electrode Load (lb.)	Current (kA)	Weld Time (Cycles, 50 c/s)	Torsion Strength (lb.-ft.)	Variance	Coefficient of Variation
200	5·7	5	10	0·51	7·3
	4·6	10	11	0·21	4·0
	3·8	20	11	0·11	3·0
350	6·2	5	12	0·27	4·3
	5·3	10	13	0·22	3·6
	4·3	15	12	0·11	2·9
500	6·3	5	13	0·27	4·1
	5·3	8	13	0·03	1·2
	4·4	10	10	0·01	1·1

Table V.—Torsion and Tension Strengths of Cold-headed Bolts Welded to 20 s.w.g. Sheet

Bolt Size	Head Radius (in.)	Electrode Load (lbs.)	Welding Current (kA)	Weld Time (Cycles, 50 c/s)	Torsion Strength (lb.-ft.)	Coefficient of Variation	Tension Strength (tons)	Coefficient of Variation
5/16 in.	0·625	750	9·0	10	20·6	4·1	0·42	7·5
			8·6	15	22·0	8·8	0·44	8·4
			8·0	20	24·4	6·9	0·46	7·2
0 B.A.	0·472	300	7·3	5	10·4	8·1	0·33	3·1
			5·8	10	11·1	8·9	0·32	3·7
			4·6	15	10·1	5·6	0·33	2·2
2 B.A.	0·370	200	5·9	5	8·1	3·9	0·29	3·1
			4·4	10	8·0	0·0	0·28	4·5

Note.—All failures in the above tests were by pulling slugs from the sheet material for both methods of testing.

Life Tests on Cold-Headed Bolts

(i) *5/16 in diameter bolts and 12 s.w.g. sheet*

A series of over 6,000 welds was made, with control tests at suitable intervals, using the recommended welding condition of 11 kilo-amperes for 10 cycles (at 50 c/s), and an electrode load of 1,250 lb. During the first 1,000 welds some wear took place on the electrode in contact with the bolt head, but additional wear up to the end of the series was negligible. The strength and consistency of the welds was maintained throughout the run. A summary of the results is shown in Fig. 5.

(ii) *0 B.A. and 2 B.A. bolts and 12 s.w.g. sheet*

A more limited investigation was made of the suitability of the 0 B.A. and 2 B.A. standard bolts by short life tests at the recommended welding conditions. The results of these tests are given in Fig. 6 and suggested that the design of head should be satisfactory for use on long production run.

Recommended Head Design and Welding Conditions

The life tests have confirmed the suitability of head design given in Fig. 4 and recommended welding conditions have been established (Table VI).

It is found that a purely empirical relationship of load, sheet thickness and bolt diameter for the tests carried out can be expressed as:

$$\frac{L}{d^2\sqrt{t}} = K$$

where L = electrode load in lbs.
d = diameter of bolt shank in inches.
t = sheet thickness in inches.
K = constant = 30,000 for B.A. sizes and $\frac{1}{4}$ in. diameter or less.
= 40,000 for 5/16 in. diameter bolts.

The loads required for sheets thicker than 12 s.w.g. will be given by those calculated for 12 s.w.g., as a further increase in thickness should have little effect on the weld size, and therefore on the forging load necessary.

CONCLUSIONS

1. Over the range tested a bolt head radius equal to twice the shank diameter is the best form for projection welding of the bolt to sheet material from 12 s.w.g. to 20 s.w.g. thick.

2. A land of 1/16 in. on the underside of the bolt head is sufficient to give adequate contact with the electrode without causing excessive electrode wear.

3. A head thickness of 1/16 in. (see Fig. 4) is sufficient to sustain the electrode load without any danger of the head shearing from the shank during welding.

Table VI.—Recommended Welding Conditions using Standard Bolts

Bolt Size	Sheet Thickness (inches)	Sheet Thickness (s.w.g.)	Electrode Load (lb.)	Welding Current (kA.)	Weld Time (Cycles, 50 c/s)	Weld Strength Torsion (lb.-ft.)	Weld Strength Tension (tons)	Coefficient of Variation Torsion	Coefficient of Variation Tension
5/16 in.	0·104	12	1250	11·3	10	58	1·9*	3·7	5·0
	0·036	20	750	9·0	10	21*	0·42*	4·1	7·5
0 B.A.	0·104	12	500	6·3	10	20	1·4†	4·5	1·8
	0·036	20	300	5·8	10	11*	0·32*	8·9	3·7
2 B.A.	0·104	12	350	5·3	10	13	0·70†	3·6	8·2
	0·036	20	200	4·4	10	8*	0·28*	3·0	4·5

* Failure by pulling a slug from the sheet. Torsion tests of welds to 12 s.w.g. sheet show torsional failure across the weld.
† Failure of bolt shank.

4. Tests have shown that the life of an electrode used in welding such bolts to sheet would exceed 6,000 welds. The ultimate limit for the number of welds which can be made before an electrode must be dressed cannot be determined, as it is dependent on the particular design of component being welded and the electrode assembly used.

5. Bolts fulfilling the above requirements, and to the dimensions given in Fig. 4, can be produced by cold heading and are ready for welding with no further treatment.

6. Care must be taken in manufacture that the underside of the bolt head is as free as possible from burrs and flashes as the presence of these causes increased electrode wear. A flat on the curved part of the head should be avoided, since if such a flat becomes too large, weld strength will fall.

7. Most of the conditions used in the main series of tests listed in Tables I to V, for the appropriate bolt design, will give welds of good and consistent strength, though more specific recommendations for welding conditions are contained in Table VI.

8. Slight variations in electrode load will have little effect on weld strength and consistency.

9. Variation in weld current can have a noticeable effect on weld strength, though the variations normally encountered will not cause the strength to fall to the minimum value when the recommended welding conditions are in use.

10. Variations in weld time which are normally met will have little effect on weld strength when the recommended conditions are used.

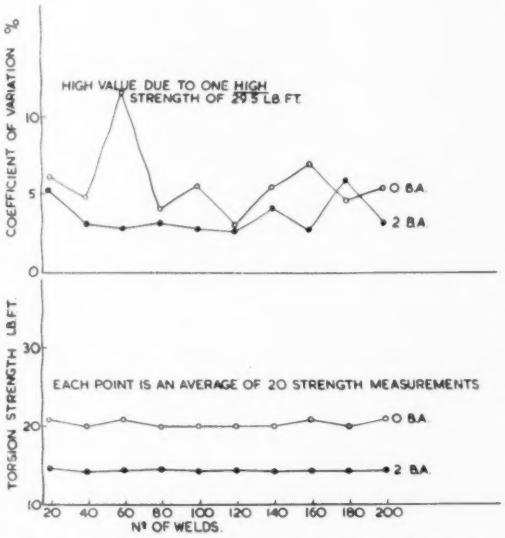

COEFFICIENT OF VARIATION %
HIGH VALUE DUE TO ONE HIGH STRENGTH OF 29·5 LB FT
0 B.A.
2 B.A.
TORSION STRENGTH LB FT.
EACH POINT IS AN AVERAGE OF 20 STRENGTH MEASUREMENTS
Nº OF WELDS.

Fig. 6. Weld strengths and consistencies for life tests on welding 0 B.A. and 2 B.A. bolts to 12 s.w.g. sheet.

APPENDIX

Use of Statistical Concepts*

Statistical means of estimating the consistency of the weld strengths have been used throughout the experimental work. The main advantage of these methods is that in assessing the scatter of results, every result is taken into consideration, whereas the older method of expressing scatter as max.-min. mean relies on the two extreme values only.

The particular values used are defined and calculated as follows:

(1) **Variance** σ^2.—This is the mean square of the deviation of individual results from the mean of those results, and is given by

$$\sigma^2 = \left[\sum(x^2) - \frac{(\sum x)^2}{n}\right] \frac{1}{(n-1)}$$

where x is an individual result, and n is the number of such individual results available.

(2) **Standard Deviation,** σ, is the root mean square of deviations from the mean, i.e. the square root of the variance. This is the fundamental measure of the spread of results about their average value.

(3) **Coefficient of Variation,** γ, is a term used to relate the scatter, as measured by the standard deviation, and the size of the values measured. It is given by

$$\gamma = \frac{\text{Standard deviation}}{\text{mean value}} \times 100.$$

The use of coefficient of variation in comparing different conditions assumes that where a larger value is being considered, a greater actual spread can be tolerated. A commonly accepted figure for coefficient of variation for a process to be considered of good consistency is 5.

* It is intended that a fuller treatment of the application of statistical concepts to resistance welding investigations will be published in this journal in the near future.

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